

# Optical Processes and Methods

# Optical Relationships

- In addition to being a wave, light can also be thought of as a particle, called a **photon**, with an energy and speed.

$$c = \lambda f$$

$$c = 3 \times 10^8 \text{ m/s}$$

Speed of Light

$$E = hf$$

$$h = 6.6262 \times 10^{-34} \text{ J}\cdot\text{s}$$

Planck's Constant

$$1\text{eV} = 1.6 \times 10^{-19} \text{ J}$$

electron-volt

$$E\lambda \approx 1240$$

Light  
energy  
in eV

Light  
wavelength  
in nm

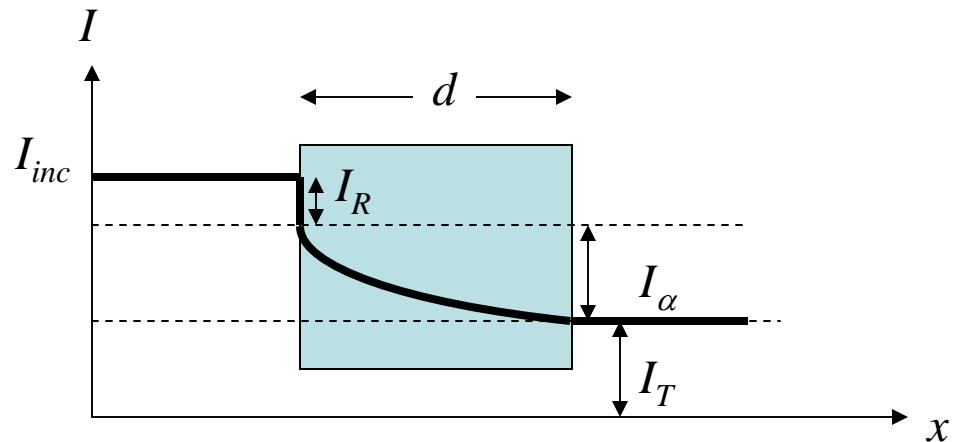
# Optical Absorption

- Light is either reflected, transmitted or absorbed.
- Absorption occurs when the energy of the incident light matches an energy level of the material.
- The electrons absorb the energy of the incident light.
- In general, there is a complicated relationship between  $R$ ,  $T$  and  $\alpha$ .

$$I_{inc} = I_R + I_T + I_\alpha$$

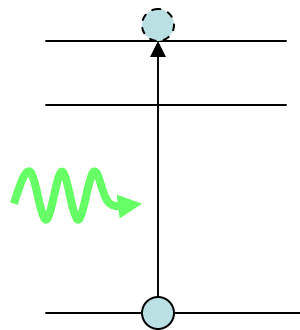
$$R = \frac{I_R}{I_{inc}} \quad T = \frac{I_T}{I_{inc}}$$

$$I_\alpha = I_{inc} e^{-\alpha d}$$

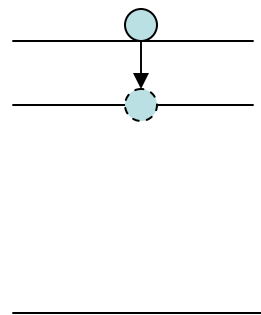


# Luminescence

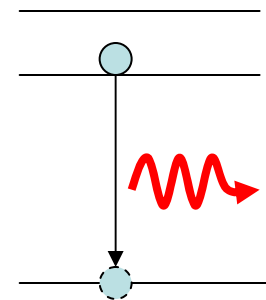
- External energy can be supplied to a material by
  - electrical current (electroluminescence)
  - optical excitation (photoluminescence)
  - electrical discharge (cathodoluminescence)
- When external energy is absorbed in a material, the excited electrons can return to their ground states by releasing the absorbed energy as light.
- This light can come from direct level to level transitions or from defects.



High energy light  
excites electrons to a  
higher energy level



The electrons relax  
to a lower level



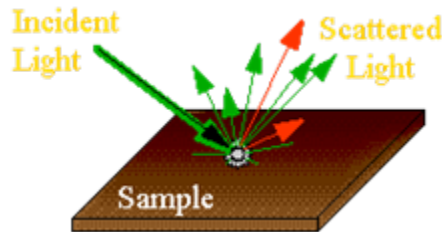
The electrons return to their  
ground state and emit light  
at a lower energy.

# Lattice Vibrations

- Atoms making up a crystal lattice can vibrate or rotate in their place.
- These oscillations can be thought of individual entities, called **phonons**, that have a characteristic oscillation frequency and energy ( $E = hf$ ).
- The energy of the vibration is dependent on the composition of the crystal and the chemical bonds.
- Lattice vibrations are also how sound waves propagate through materials.
- If the vibrations are in the direction of the lattice, they are called longitudinal vibrations.
- If they are in perpendicular to the direction of the lattice, they are transverse vibrations.
- Transverse vibration energies are in the order of tens of meV.

# Raman Scattering

- The Raman effect arises when the incident light excites molecules in the sample which subsequently scatter the light.
- While most of this scattered light is at the same wavelength as the incident light, some is scattered at a different wavelength.
- This *inelastically* scattered light is called Raman scattering.
- The main medium for this energy change are the lattice vibrations.



# Non-linear Optics

- When light passes through a material, it interacts with the atoms around it.
- The electric field associated with the light wave will distort the electrons in their orbits creating a polarized state.
- The material polarization in turn affects the light propagating through it.
- For low intensity light, this polarization is linearly dependent on the electric field and only the intensity of the light changes.
- However, for high intensity light waves, the dependence becomes non-linear.
- The non-linearity creates harmonics of the light wave.

The incident electric field

$$E = E_0 \cos \omega t$$

The polarization response of the material

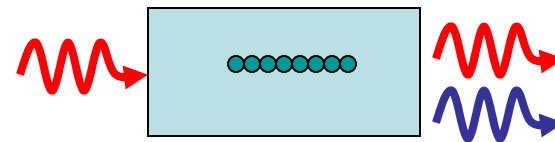
$$P = a_1 E + a_2 E^2 + a_3 E^3 + \dots$$

Second Harmonic Generation

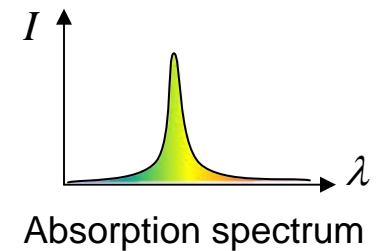
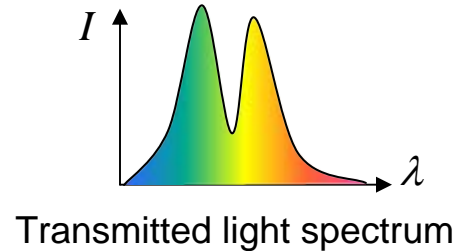
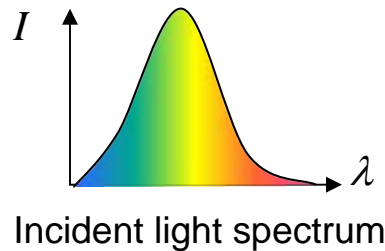
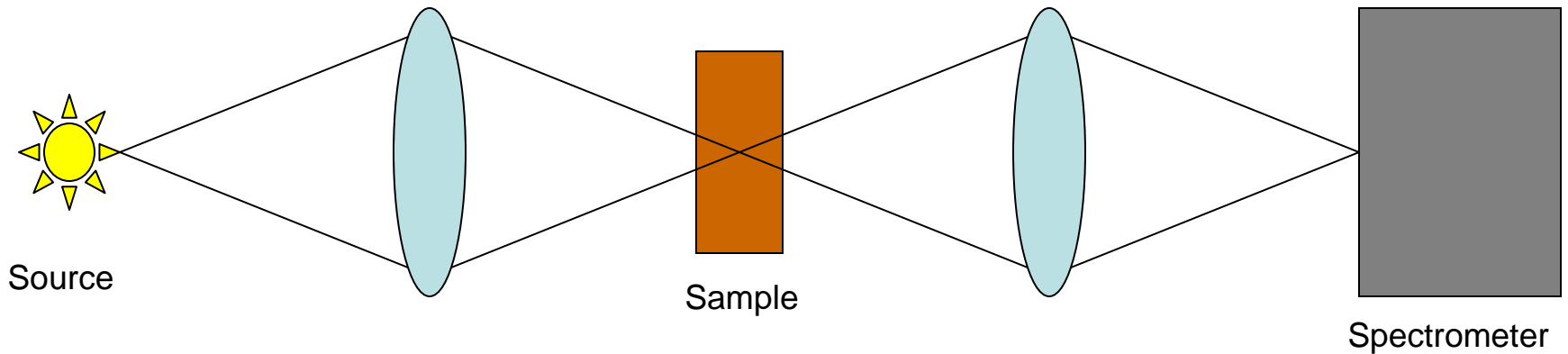
$$P = a_2 E^2 = a_2 (E_0 \cos \omega t)^2$$

$$P = a_2 E_0^2 \cos^2 \omega t = a_2 E_0^2 (1 + 2 \cos 2\omega t)$$

2<sup>nd</sup> Harmonic at  $2\omega$

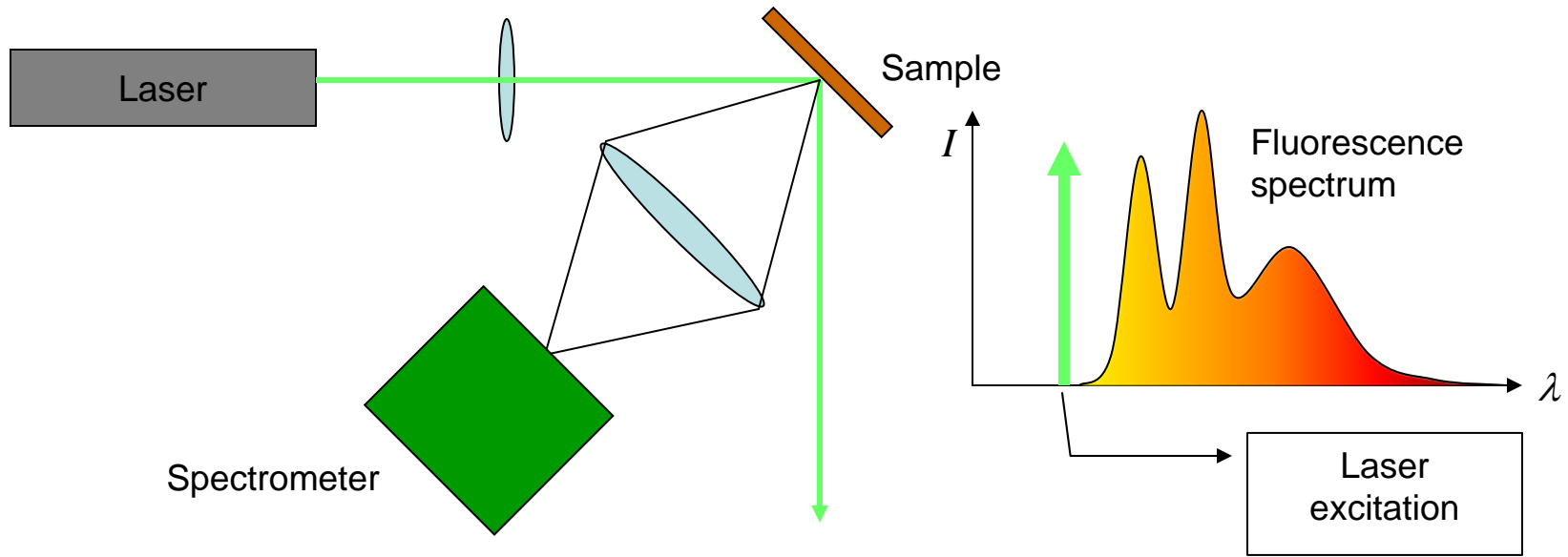


# Absorption Spectroscopy



- Measures the absorption coefficient.
- The result is a combination of a number of processes that go on in the sample.

# Fluorescence Spectroscopy



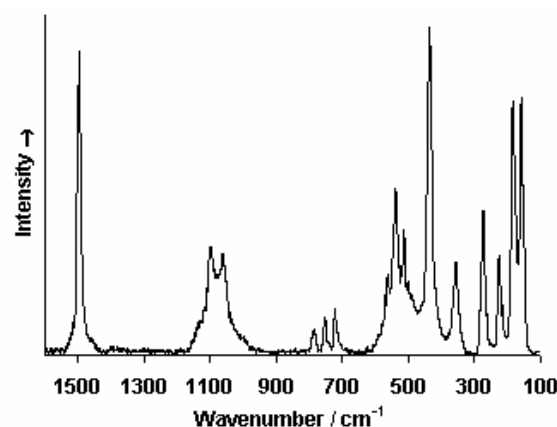
- The laser excites an electronic transition.
- Light at various wavelengths are emitted as the electrons relax and return to their ground states.
- It is sensitive to electronic transitions.

# Excitation Spectroscopy

- Same setup but now change the excitation wavelength and detect at a single wavelength.
- Used for precision measurement of molecular absorption lines.

# Raman Spectroscopy

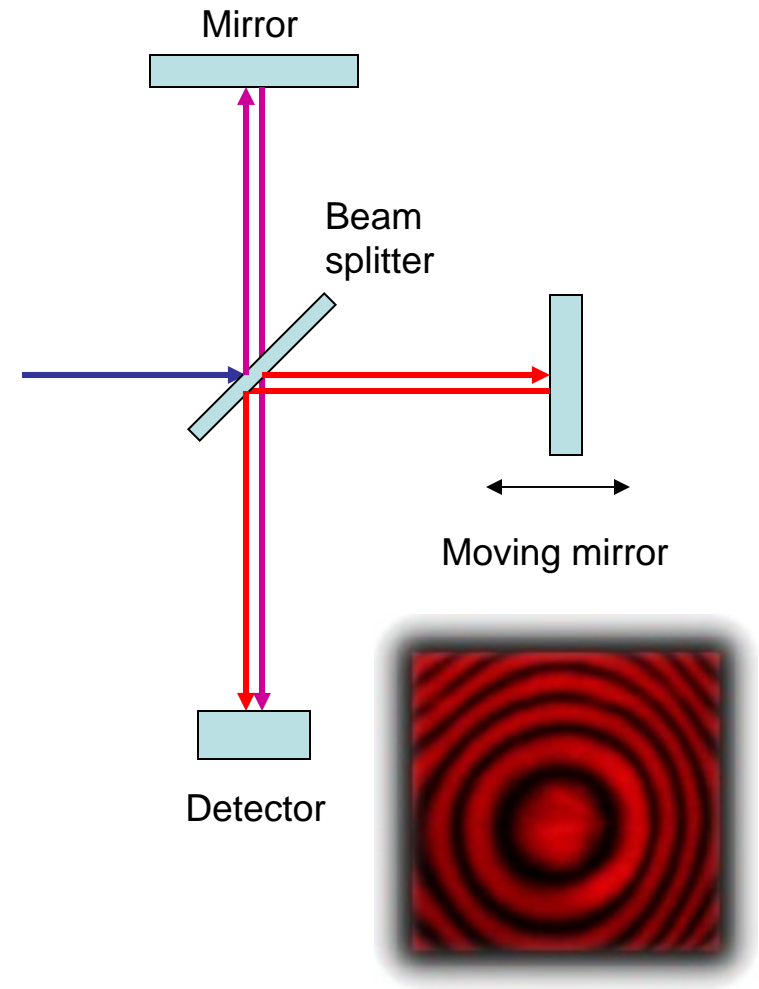
- The setup is similar to fluorescence spectroscopy.
- However, since the Raman scattering lines are very close to the laser excitation, narrow band lasers, precision filters and double monochromators are used.
- Raman scattering results from the change of the excitation laser wavelength by lattice vibrations.
- The lattice vibrations are sensitive to the chemical bonds in the sample.
- It is used in chemical analysis, process control and thin film quality measurements.
- The units are in wavenumbers ( $k = 2\pi/\lambda$ )



Raman spectrum of  
Malachite Green

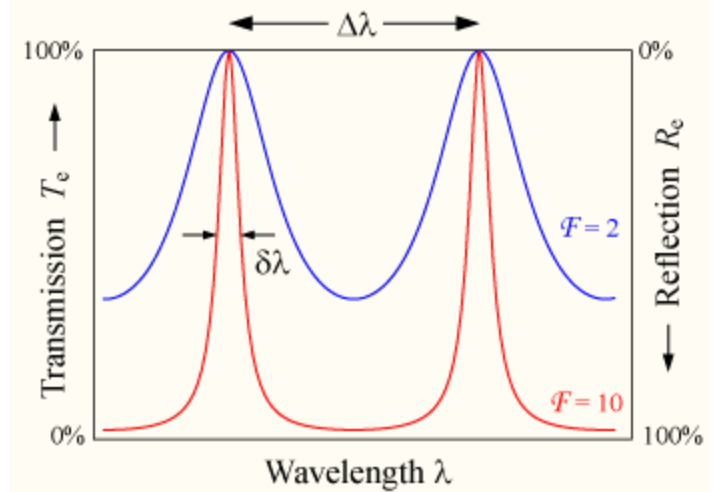
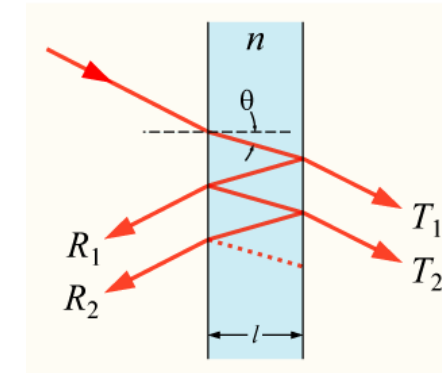
# Michelson Interferometer

- The idea is to detect the difference in the arrival times of two beams by their interference.
- The arrival time is also equivalent to path length.
- This technique can be used to test surface quality and flatness.



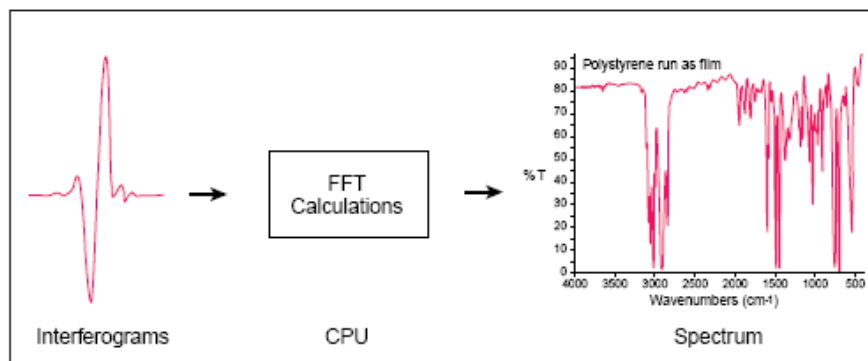
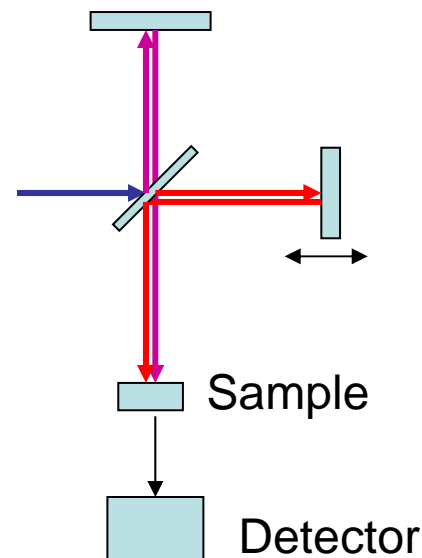
# Fabry-Perot Interferometer

- It is based on thin film interference.
- Since constructive and destructive interference is dependent on the wavelength of the light and the length of the interferometer, it can be a very precise method of wavelength measurement.
- The reflectivities of the surfaces determine the *fineness* of the interferometer (the sharpness of the transmitted lines)



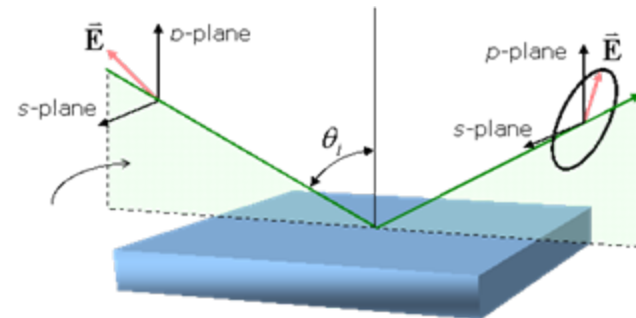
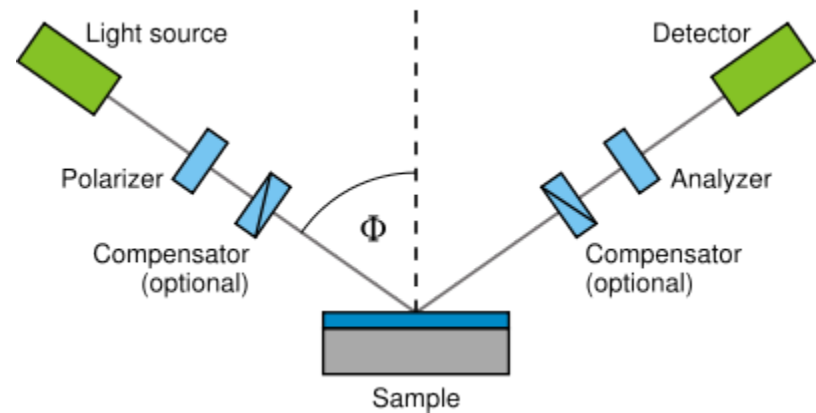
# FTIR Spectroscopy

- Fourier Transform Infra-Red Spectroscopy
- It is a combination of IR absorption spectroscopy and a Michelson interferometer.
- The absorption is recorded as a function of time (as the mirror in one of the interferometer arms is moved).
- The resulting interferogram is then Fourier transformed in to frequency space to obtain an absorption spectrum.
- The spectrum is sensitive to the vibrations of the molecular bonds of the sample material.



# Ellipsometry

- Ellipsometry measures the change of the polarization of a beam upon reflection or transmission.
- Using equations that relate reflection coefficients to polarization, the technique gives direct measurement of the complex dielectric constant of the sample which includes information about the index of refraction and the absorption coefficient.
- Both of those quantities will depend on the surface composition, thickness and morphology.
- One can measure thicknesses much less than the wavelength of the light used.

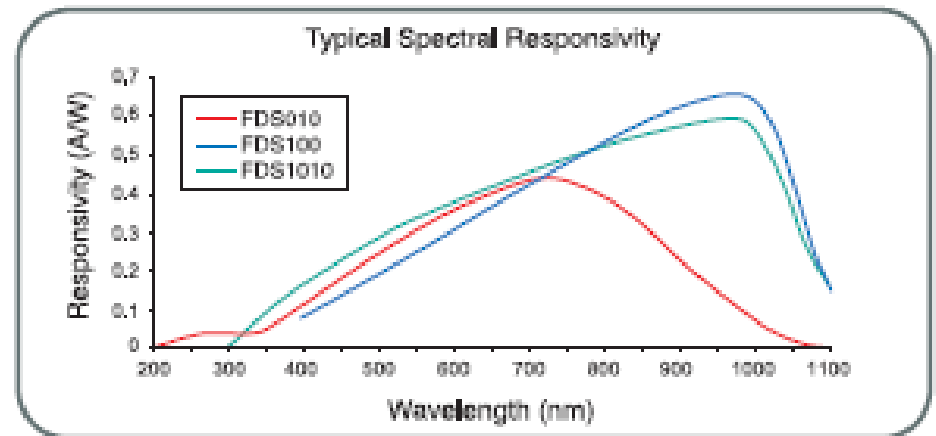


# Detectors

- Photodiodes
- Avalanche Photodiodes
- Photovoltaic cells
- CCDs
- Photomultipliers

# Photodiodes

- Uses an active, undoped layer sandwiched between a p- and an n-type semiconductor.
- Light incident on the undoped layer excites electrons and holes.
- Under bias, electrons are swept to the p-type layer and holes to the n-type and create a current that is proportional to the incident light intensity.
- Light has to be absorbed in order for current to be created, so the wavelength range of a PD is in its absorption region.
  - Si: 200 - 1100 nm
  - Ge: 400 – 1700 nm
  - InGaAs: 800 - 2600 nm



Typical Si Photodiode response curves

# Avalanche Photodiodes

- Under high reverse bias, a photodiode can show high gain.
- Basically, each excited electron has enough excess energy to excite another electron which in turn can excite another, etc.

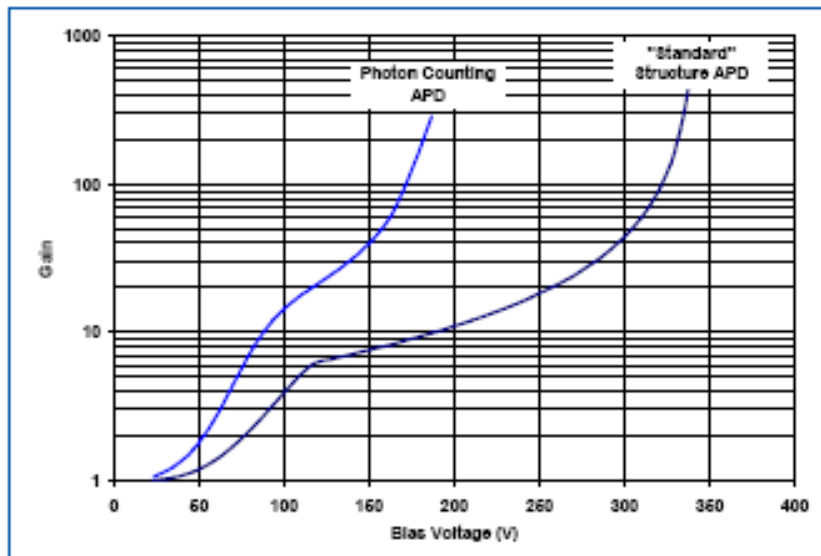
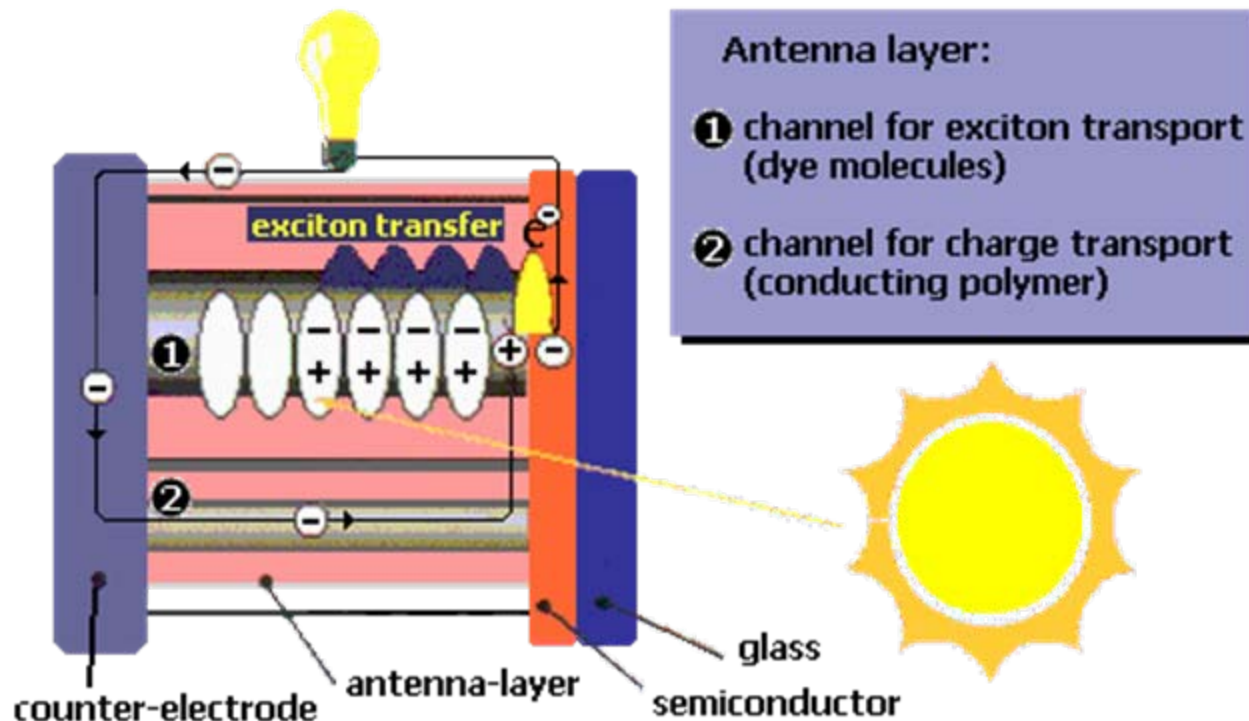


Figure 2 Gain vs Bias voltage

The Gain as a function of the bias voltage varies with the structure of the APD

# Photovoltaic Cells

- Same principle as a PD but no n- or p-type layers.



# CCDs

- CCD stands for Charge Coupled Device.
- It is a combination of a light sensor array (such as a photodiode array) and a capacitively coupled read out mechanism that allows sequential reading of the optical signal at each element of the array with the aid of a clock signal.
- Since they can be fabricated in to large 2 D arrays and have excellent gain and background noise characteristics, they are used as image sensors.

# Photomultiplier Tubes

- A vacuum tube houses a series of dynodes and an anode.
- Photons incident on the cathode generate photoelectrons.
- These electrons are amplified in successive dynode stages by secondary electron emissions.
- Gains up to  $10^8$  can be achieved, enabling single photon detection.
- PMTs are sensitive in the UV and visible ranges.

